MODEL-BASED OPERATION OPTIMISATION OF GLASS MELTING FURNACES

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The present paper is aimed at discussing the utilisation of mathematical modelling techniques in the control of glass melting furnaces. Several recent developments of model-based control strategies are discussed. Physically-based modelling tools for furnace operation optimisation are presented and its applicability for automatic control, supervision and co-ordination systems are discussed. An application example in which a recently developed model-based algorithm is used for a glass melting endport furnace on-line operation optimisation is described. The visualisation of non-accessible process data through the use of a three-dimensional modelling tool is also exemplified.

1 - INTRODUCTION

The pressure to improve the operation efficiency of glass making plants is increasing as some major social, economic, energetic and environmental constrains are more and more affecting the glass industry. Growing awareness for safer, cleaner, cheaper, lighter, faster and better production has turned the investment in Research and Development, a strategic priority for the modern glass industry. This paper is aimed at discussing the model-based control technologies for glass furnace operation optimisation as part of this R&D effort.

Special demands in refractories, burning systems, furnace architecture, preheating devices, instrumentation and control are good examples of fields where the technology transfer from other industrial processes is not straightforward.

This is nowadays happening in the field of control technologies, when recently developed physically-based mathematical models start to be part of advanced control systems and the development of new control and operation strategies is one of the safest ways to improve the equipment efficiency.

1.1 - The need of modern control systems for complex processes

The development of advance control and supervision systems are becoming an important factor in helping glass industry capable to achieve strategic developments in the following directions (1, 2): to market new glass products (ultra-light containers, ultra-thin panels etc.); to meet environmental regulation at low cost (avoiding the use of expensive pollution controlling devices); to protect the workers environment and safety (meeting emerging social); to reduce the equipment size, complexity and degradation (lowering investment costs); to decrease the energy and raw materials consumption (lowering operation costs); to improve the product quality (keeping low costs); to flexibilize the production chain (responding to the marketing demands).

1.2 - The need of modern control systems for sophisticated glass products

Future trends in glass industry are strongly related with the development of new products. In the flat glass sector the markets are more and more demanding for multi-functional glazing. In container glass the response to the competition of metals and polymers containers seems to be the development of lighter containers with increased strength and durability. In the special glasses sectors, the industry is subjected to a board range of new demands. All these requirements will impose special needs to improve the operation process and introduce new complexities in the production chain. This is another reason which explains why control systems in glass industry are becoming a strategic R&D topic (3).

2 - GLASS FURNACE MATHEMATICAL MODELLING

In this chapter a simple and short classification of the modelling tools used in advanced control strategies is proposed to help the understanding of the further presentation of model-based control algorithms.

Identification models - In this models, process data is treated typically by black box module where standard functions are adjusted to reproduce data identified from the industrial system. The flexibility to handle a large number of industrial systems and the proximity to the industrial system are the main advantages of these models. Following the same approach, more recently neural networks being used to build identification models. Application examples in glass industry: simultaneous temperature and outlet gas composition on-line prediction to be

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** IrRADIARE, Research & Development in Engineering and Environment, Ltd. - 2780 Oeiras, Portugal used in the regulation of fuel injection and air/fuel ratio.

Single equation physically-based models - Simple laws are adjusted to describe the behaviour of industrial systems through the correlation of process data. From a previously known relation between a process parameter and a particular feature of the industrial system, a mathematical function is set-up and adjusted with measurements. Application examples in glass industry: instantaneous determination of fuel efficiency using temperature and mass flow rate measurements.

2.1 - Physically-based simulation models

These models are based on complex numerical solvers for the equations that govern the behaviour of the relevant physical phenomena occurring in the industrial equipment. The practical use of these models in control of industrial glass melting furnaces is presently growing as the cost of these models in control of industrial glass melting furnaces is presently growing as the cost of associated hardware is becoming lower. However, only very recently dedicated control systems based on these modelling tools start being available (4, 8). Examples of possible applications may be given as follows:

- *Optimal operation strategies.* The on-line generation of operation scenarios to be used in the automatic search of optimal working conditions.
- *Process data reconstruction.* Dedicated three-dimensional numerical models can be used to calculate, off-line, non accessible process data.
- *Expert systems.* Sophisticated modelling tools may be used to build or to embody knowledge-based systems part of expert systems which can be used to assist the operation.
- *Tomographic model based observation.* Dedicated three-dimensional models can be used to reconstruct fields of relevant variable using as input the current state of the furnace operation.
- *On-line operation optimisaton.* Simplified and dedicated multi-dimensional models when coupled with optimisation algorithms can be used for the set-up of on-line optimisation loops.

3 - MODEL-BASED PREDICTIVE CONTROL OF GLASS-MAKING SYSTEMS

In this chapter some examples of identification model-based predictive controllers and of physically-based model utilisation in advanced control strategies are given.

Identification-model based predictive controllers

Traditionally, most industrial processes were controlled in a primary loop by loop basis where several local set-points were regulated using adjusted Proportional, Integrative, Derivative (PID) controllers. This was, mostly, a single-input/single-output approach. However, accordingly to the current demands of quality, flexibility, efficiency and safety imposed to the industrial process, classical control strategies proved to be insufficient. Luis Ayala (9) presented a structured logic controller for the forehearth temperature control. In this work, experiences on the development of PID based controllers are compared with structured logic based controllers. PID controllers proved to be unable to adequately satisfy all the control requirements without operator intervention due to the effect of disturbances from preceding zones. Feedforward control was presented as an alternative to accommodate the upstream disturbances. Careful modelling of the forehearth process was proposed. The use of adaptive self tuned or, alternatively, on-line tuned model-based controllers was investigated.

A similar problem in the glass melting production is the regulation of the glass temperature in float glass melting tank outlet. The heavy glass-melt inertia plays a decisive role in the behaviour of the outlet temperature. Takafumi Ito and Shoji Inabayashi (10) proposed an adaptive model-based control strategy to reduce temperature instability in a float glass melting furnace. A process computer, networked to a workstation, was used to calculate the estimated values of the identification model. Model analysis and controllers tuning were done in the workstation. Promising results were obtained, although, stabilising control by simple identification models does not allow the optimise the operation as required for such a complex process. Artificial intelligence techniques were suggested in (10) as a basis for the development of optimal process control.

A fully black-box approach was followed in the development of an adaptive predictive control procedure for the glass melting furnace bottom temperature by J-F. Simon and V. Wertz (11). Historic treatment of process data reporting glass quality levels was done to find the correct temperature set-points, specially bottom temperature set-point, for good product quality. A cascaded control strategy in three levels was proposed. The major difficulties are: to handle the large thermal inertia of the melting tank and to balance the big relative importance of perturbations. An identification model was developed and used for continuous testing of the best crown temperature profile to be used for the more stable bottom temperature reponse. A feedforward compensation of predictable variations and a feedback compensation of the unpredictable perturbations were set. A model adjustment procedure was used to keep the model predictions closer to the furnace behaviour. This controller was tested with promising results in two cross fired furnaces. A similar approach was also proposed by Toichiro Nakagawa and Tokio Kimura (12) to control the bottom temperature, together with a suggested fusion, in a multi-variable hybrid control system, of qualitative and quantitative process data.

Aimed at overcoming the difficulties associated to the regulation of fully multi-input/multi-output processes in basis of conventional identification-model based controllers, Shi Jing Zou and Chen Yong Yi (13) proposed a Fuzzy Logic Controller to regulate a glass tubing process. A single fuzzy logic control loop has been created to regulate the glass tubes outside diameter in a danner process.

A very interesting first attempt of combining, in a control and supervision hierarchical system, PID based local control loops, neural network based predictive zonal control and a fuzzy logic was presented by D.K. Pirovolou and co-authors (14). This methodology was applied to the optimal control of a «gas hearth» used in manufacturing of automobile door windows, a process where the quality requirements are very strict. The so-called «gas hearth» in a sort of tunnel kiln which can be devised into a number of zones where local control loops for top and bottom temperatures and pressure were used. A polynomial neural network was used as an identification model capable to handle with the process dimensionally and complexity. Satisfactory results in determining the overall process set-points and local corrections to the PID controllers set-points were reported in (14). An additional important feature was the capacity of preventing operation disturbance propagation along the tunnel kiln limiting the impact of production instabilities and uncontrolled fluctuations.

3.1 - Physically-based model utilisation in advanced control strategies

Physically-based models present three major advantages for use in control:

- the physically-based models allow the diagnostic of the industrial system operation beyond the available process data, like the thermal efficiency, for instance.
- the strongly coupled systems (highly multi-input/multi-output systems) are not easily accommodated by identification models, even using neural networks. The spatial resolution and the coupled character of physically-based three-dimensional models make it to be a priority tool for the treatment of strongly multi-input/multi-output situations.
- the physically-based models rely on the solution of the actual physical phenomena. Thus, its predictive capability allows to evaluate the system reactions under operating conditions.

The recentness of the physically-based models use in industrial problems solution may explain why only a very few applications in control of glass melting units have been presented yet. Below some pioneer works in these field are referred.

E.D. Farmer (15) developed a model-based adaptive control strategy for the optimal control of the fuel efficiency in the glass melting furnace. This system was aimed at minimising, on-line, the fuel consumption. A physically-based allows to visualise the instantaneous energy efficiency and estimate the NOx formation. A conventional adaptive control technique was used to maximise the energy efficiency, namely taking profit from the use of distributed burner control.

R. Sims presented (16) a supervision system for the forehearth operation. Set-points for the local control loops were carried out by the supervision system. An on-line adjusted physically-based model is used in three main algorithms: temperature stabilisation, temperature homogenising, job change operation assistance module. Results of the utilisation of these three functions were presented in (16).

An other example of the physically-based models use in glass melting systems control is given by Nicolas Vanandruel (and co-authors) (17). In that paper, a control function is proposed in basis of results of non-steady three-dimensional modelling of a glass melting tank. This work was aimed at finding the time reponse constants of temperature and velocity at several locations where measurements in real conditions would not be possible.

R. Bauer (and co-authors) has shown (18) as the current improvement of the capabilities of mathematical simulation models can be useful for control, specially to improve the product quality. In that work, sophisticated modelling tools have been used to obtain operation rules. Those rules were used to form a knowledge-base system part of an innovative control strategy aimed to ensure high levels of glass quality. A fuzzy logic controller has been adopted to supervise the furnace operation. A practical example where the response of a glass-melting furnace to colour changes has been optimised through that control strategy is presented in (18).

The overall glass melting chain is a complex and sensitive system. Its reactions are broadly zone-to-zone correlated and strongly non-linear. These aspects are driving the development of sophisticated model-based control strategies, namely using in neural networks, fuzzy control theory and physically-based models, as it could be drawn from the above described contributions.

4 - APPLICATION EXAMPLES

Some examples of model utilisation for glass melting operation optimisation are given in this paper. The first two application examples concern the utilisation of a physically-based dynamic model for both on-line optimisation and stabilisation. An example showing the three-dimensional model capabilities for on-line assessment of an oxy-fuel melting furnace performance is also given.

4.1 - A physically-based dynamic model based control algorithm

A physically-based transient modelling tool coupled with an optimisation algorithm was set up to maximise some essential but non-sensored furnace operation parameters.

4.2 - The physically-based dynamic model

Due to the strong interaction between the several components of the glass furnace system, namely re-

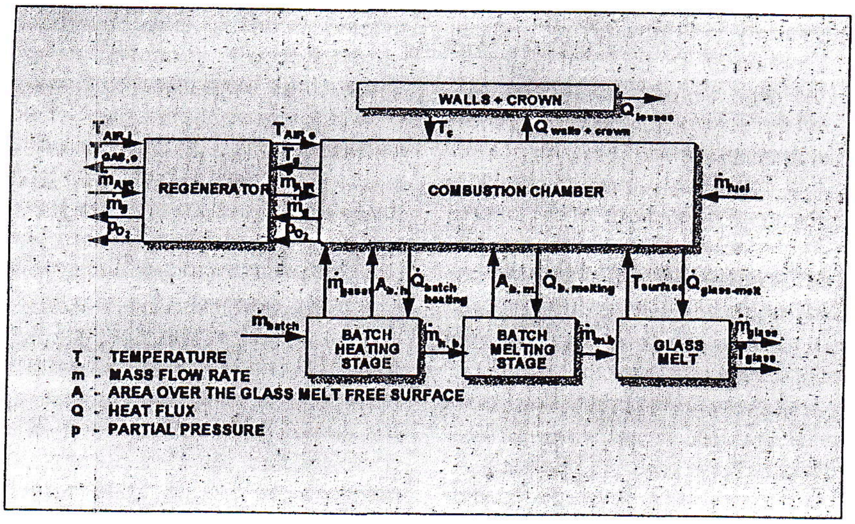


Fig. 1 - Glass end-port furnace considered subsystems for physically-based time-dependent modelling.

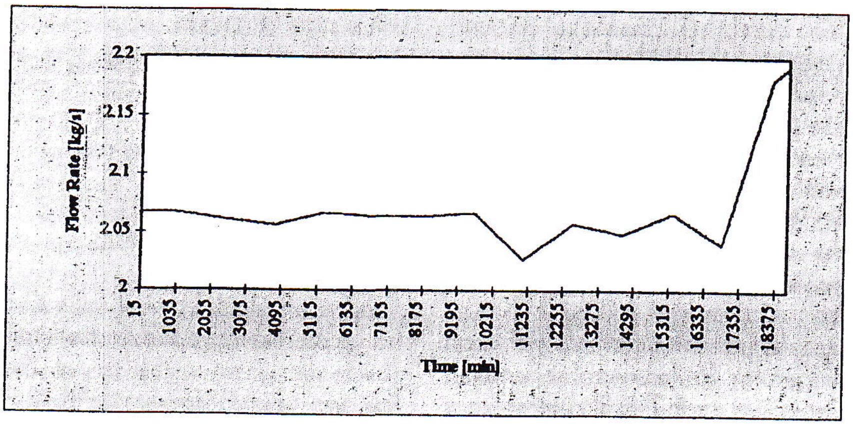


Fig. 2 - Furnace pull rate (kg/s).

specting its dynamic behaviour, the developed model is based on the calculation of the heat and mass transfer between all the furnace considered subsystems (figure 1).

The regenerative chambers were simulated as an one-dimensional system along which energy and mixture fraction convective/diffusive transport equations were solved. The gas emissivity is calculated through the grey gases mixture procedure (19). The convective heat transfer coefficient was calculated using a standard correlation (20).

In the combustion chamber, the main heat transfer process is the radiative exchange between the hot gases and the enveloping surfaces. In the present simulator the radiative transfer is solved through the radiosity equations (21). The batch floating over the glass-melt, is in the present model, divided in two stages, the heating stage and the melting stage.

The solution procedure is based in the calculation of non-steady heat and mass for each one of the above referred components.

4.3 - The on-line operation optimisation algorithm

Two merit functions were calculated from the above described dynamic model results: 1) overall furnace performance; 2) furnace output stability.

The performance merit function is continuously calculated from the above described time-dependent model results. An index is computed through heuristic relations which make possible an on-line classification of the furnace performance. The relevant parameters were considered in the development of this performances merit function. The computation of the glass outlet temperature deviation respecting to a given target is considered to classify the furnace operation stability. Two dedicated optimisation algorithms were developed to find optimal operating conditions for the furnace operation. These algorithms are based on the so-called «hill climber» approach. They are designed to maximise the stability and performance index. The modelling tool is used to supply data to the optimisation algorithm concerning the classification of near future operation scenarios.

4.4 - Application results - performance maximisation

A model-based optimal control strategy was tested for future on-line application in the operation optimisation of a regenerative end-port furnace. The furnace pull is given by Fig. 2. The operating conditions with and without the optimal control algorithm are shown in Fig. 3 to 5 where the profiles of fuel flow rate, glass temperature and glass quality index are shown. The proposed control strategy is aimed at embodying a supervision system capable to give to the operator the near future main operation parameters able to ensure glass optimal production.

4.5 - Application results - stabilisation

The above described model-based optimal control strategy was tested for the stabilisation of the same furnace operation.

A stepwise change in the pull rate is introduced to exemplify the algorithm use. The consequences for the furnace operation of that sudden change were simulated under a constant crown temperature profile. As shown in Fig. 6, the outlet glass temperature decreases until a new temperature level, eventually far from an operation target. Using the developed model-based optimal control strategy, the glass outlet temperature can be stabilised by means of feedforward actuation in the

Fig. 3 - Fuel inlet rate (kg/s).

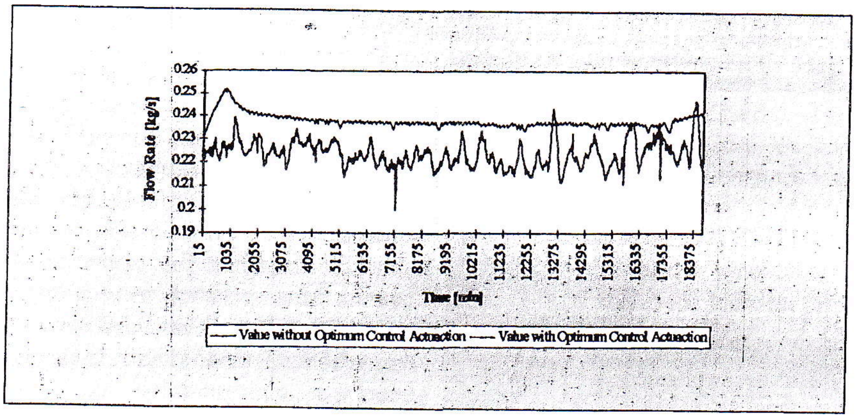


Fig. 4 - Outlet glass temperature (=°C)

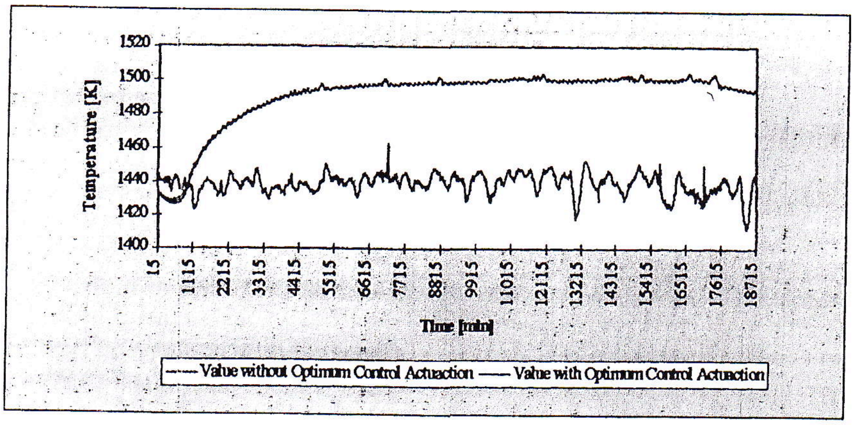


Fig. 5 - Glass quality index.

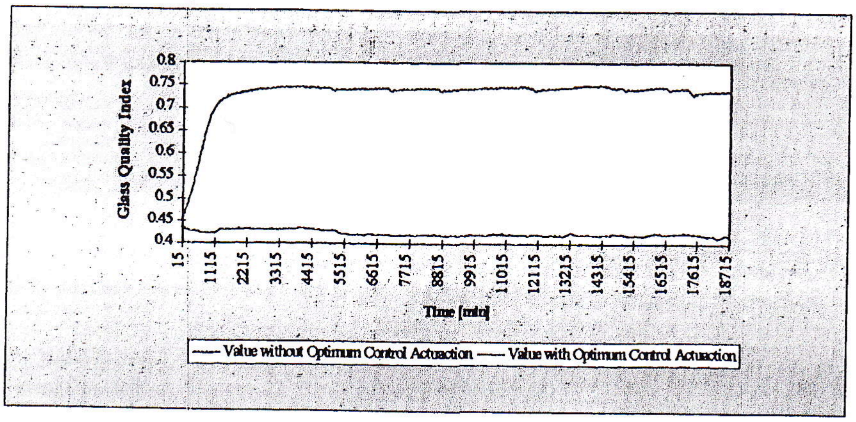
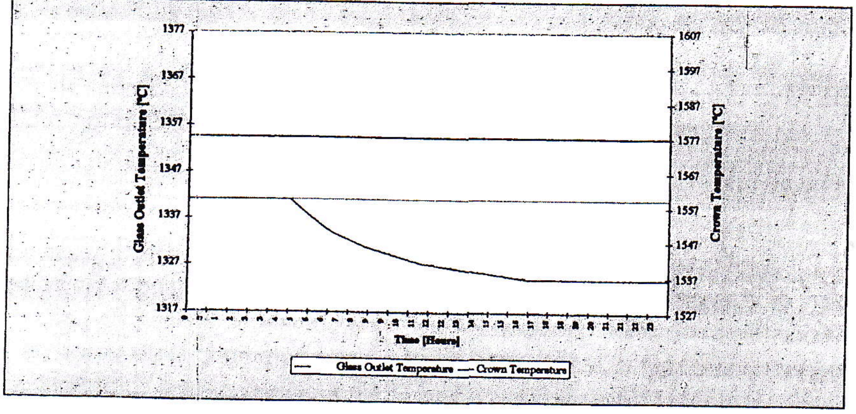


Fig. 6 - Crown temperature, glass melt outlet temperature predicted and targeted.



crown temperature. The effect of this action is illustrated in Fig. 7 where the stabilisation of the outlet glass temperature is shown to be achieved, with the calculated crown temperature profile. The proposed control strategy allows to give to the operator the near future profiles of the furnace parameters able to ensure stable glass production.

4.6 - Three-dimensional simulation of an oxy-fuel furnace operation

A three-dimensional mathematical modelling describing the physical phenomena occurring in a glass tank furnace has been developed. This model is based on the solution of conservation equations for mass, momentum, energy and combustion related chemical species, and comprises three main coupled sub-models: the combustion chamber, the batch melting and the glass tank (23). The three main sub-models were coupled by a cyclical iterative way (24).

Combustion chamber model incorporates physical modelling for the turbulent diffusion flame, soot formation and oxidation, NO formation and dissociation, particles entrainment, formation and transport and radiative heat transfer. The time-average equations for the conservation of momentum were used as well as the equation for the conservation of energy (22).

Batch melting model incorporates physical modelling for the heat transfer and melting down process. The conductive heat transfer occurs only in batch depth direction (23). Glass tank model incorporates physical modelling for the flow and heat transfer of the molten glass (24).

4.7 - Application results - evaluation of NOx formation critical region

The above described three dimensional model was applied to the evaluation of a large size oxy-fuel glass melting furnace. In figure 8, a vertical plane cutting one of the oxy-fuel burners was selected, as an

Fig. 7 - Crown temperature, glass melt outlet temperature predicted and targeted, using the model-based feedforward control algorithm.

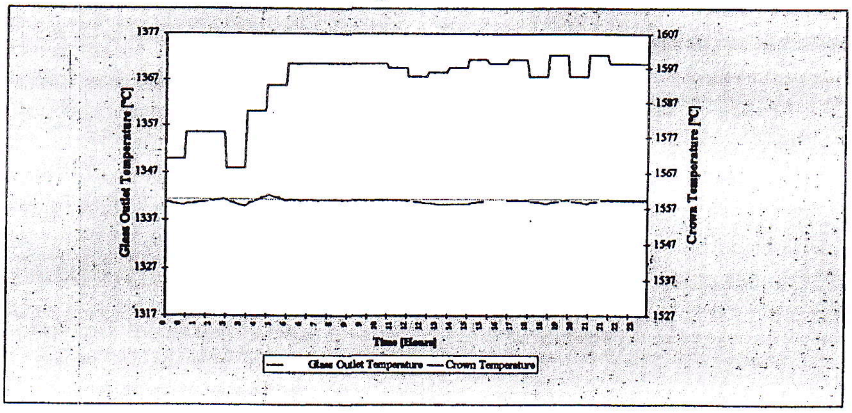
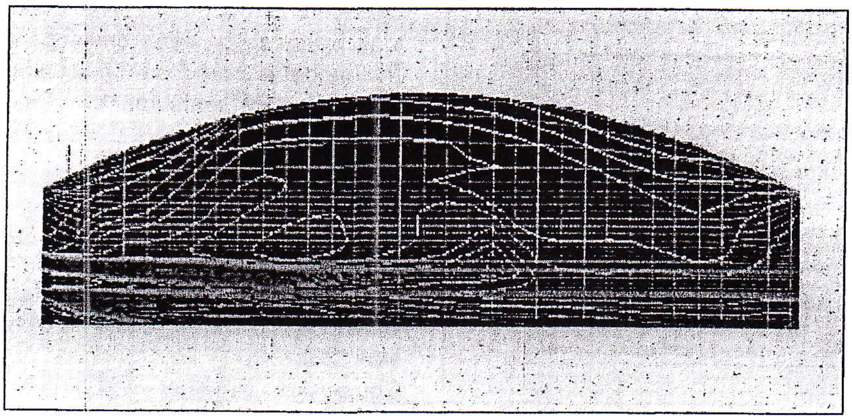


Fig. 8 - Predicted NOx concentration inside a large size oxy-fuel combustion chamber.



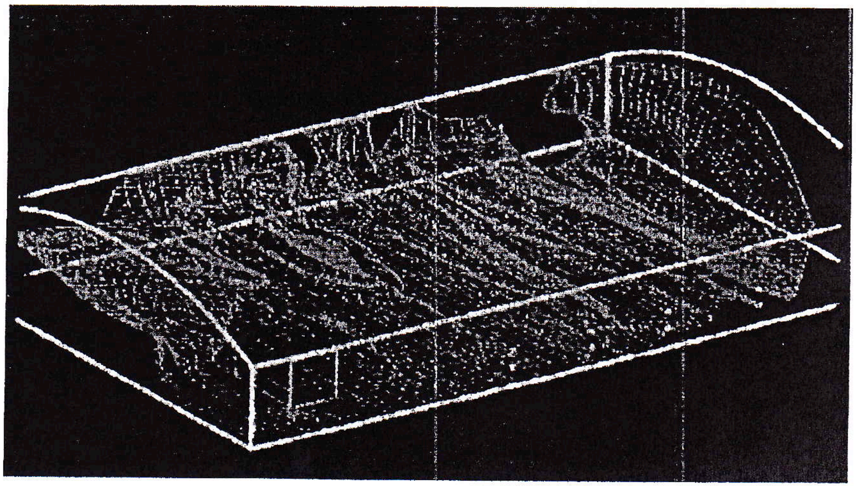
example, for the visualisation of the NOx concentration inside the combustion chamber. In this figure the location of the high concentration gradients are well apparent near the flame envelope.

The availability of such a result may be specially useful for the understanding of the NOx formation mechanisms under actual operating conditions. This may be specially important as it is know that the actual high NOx formation rates may present completely different patterns inside an oxy-fuel combustion chamber when comparing with air-fuel conventional combustion systems. The actuation on the furnace operating conditions for reduction of NOx emissions in an oxy-fuel melting furnace, specially a large one, may be a difficult task. The availability of decision aiding tools to the furnace operation team may be an important contribution to easy that job. The developed three-dimensional models is aimed, among other applications, at embodying a model-based knowledge system dedicated to the help the furnace operation optimisation.

4.8 - Application results - visualisaton of the particles distribution inside the combustion chamber

In Fig. 9, a three dimensional visualisation of the above considered furnace is presented to show the spatial distribution of particles inside the combustion chamber of a glass melting furnace. This capability may be specially useful as it is very difficult to estimate the behaviour of the particles entrainment, formation and transport mechanism inside a combustion chamber. The actuation on the furnace operating conditions for reduction of particle emissions may be a difficult task without a simulation tool helping the furnace operation team. The use of a physically-based three-dimensional modelling tool as the one here presented is a promising alternative to the development of particle emission databases which would be expansive and eventually not applicable but for a short range of operating scenarios.

Fig. 9 - Predicted particles concentration inside a large size oxy-fuel combustion chamber.



5 - FINAL REMARKS

Glass industry is aimed at making glass products at a quality/cost ratio as high as possible. The authors believe that advanced control, supervision and co-ordination tools may be in the near future an important factor to help glass industry to increase that ratio.

This paper concerns the use of mathematical modelling tools in the development and operation of advanced automatic systems for control, supervision and co-ordination of the glass melting process. Several recent developments and applications were discussed as well as some application examples were described. From these examples, it may be concluded that modelling tools use in control tend to be one of the more actives R&D fields in glass melting process technology, as the following proposed ones:

- continuous development of advanced physically-based multi-dimensional mathematical models with high levels of performance to be used in strongly multi-input/multi-output/multi-task automatic controllers and supervision systems.
- development of fusion algorithms combining the advantages of physically-based models and advanced identification models as neural networks based ones.
- development of advanced optimisation algorithms capable to use in a economic way model-generated data in process control and optimisation.
- development of interconnection strategies for hierarchical use of model-based algorithms for the development of plant-wide co-ordination and supervision automatic systems.

Plant wide association of sophisticated unit controllers with supervision expert systems may lead the development of automatic co-ordination systems making possible the future realisation of computer integrated glass manufacturing.

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